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The acquisition of survey knowledge for local and global landmark configurations under time pressure

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Abstract

The influence of stress states on cognition is widely recognized. However, the manner in which stress affects survey knowledge acquisition is still unresolved. For the present study, we investigated whether survey knowledge acquisition during a stressful task (i.e., under time pressure) is more accurate for the mental representation of global or local landmarks. Participants navigated through virtual cities with a navigation aid and explicit learning instructions for different landmark configurations. Participants judgments of relative direction suggest that global landmark configurations were not represented more accurately than local landmark configurations and that survey knowledge acquisition was not impaired under time pressure. In contrast to prior findings, our results indicate the limitations of the utility of global landmarks for spatial knowledge acquisition.

Everyday navigation often occurs under time pressure and with uncertainty regarding the surrounding environment. Imagine you are on your way to a job interview, but the train is late. After you arrive at the train station, you will have to rush through an unfamiliar environment in order to reach the interview on time. In such situations, you might experience an acute stress response, negative emotions, and/or intrusive thoughts with respect to being late for appointments (Zimring, 1981) or getting lost in the city (Lawton, 1994). In addition, acute stress responses can substantially influence cognitive functioning (e.g.,

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Lupien, Maheu, Tu, Fiocco, & Schramek, 2007), as well as orientation in and mental representation of large-scale spaces (e.g., Duncko, Cornwell, Cui, Merikangas, & Grillon 2007; Evans, Skorpanich, Gärling, Bryant, & Bresolin, 1984; Richardson & Tomasulo, 2011; Gardony, Brunyé, Mahoney, & Taylor, 2011). However, navigation research has not considered the manner in which stress affects survey knowledge acquisition during navigation. The primary goal of this project is to answer fundamental questions in spatial cognition with implications for the improvement of stress-resilient navigation systems that support survey knowledge acquisition. According to Siegel and White (1975), survey knowledge results from the mental integration of familiar routes and local landmarks over time. Recent evidence has shown that survey knowledge acquisition can benefit from the presence of global landmarks as well (Li, Korda, Radtke & Schwering 2014; Li, Corey, Giudice, & Giudice, 2016; Schwering, Krukar, Li, Anacta & Fuest, 2017). However, the issue of how global landmark configurations differ from local landmark configurations when integrated into a common survey representation is still open. Furthermore, previous research remains unclear in the case of learning in a stressful navigation context. The present study examined stress effects on learning the relations among local landmarks (e.g., a shop along the route) as compared to global landmarks (e.g., a tower in the distance) during an egocentric navigation task. We build on prior empirical findings from the general psychology literature that have indicated an impairment of working memory (e.g., Oei, Everaerd, Elzinga, van Well, & Bermond, 2006) and/or inattention to global landmarks (Gardony et al., 2011) under acute stress exposure. Following these findings, we expect stress to adversely affect survey knowledge acquisition because of the importance of working memory for integrating spatial information over time (Friedman & Waller, 2008; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Meilinger, Knauff, & Bülthoff, 2008) and the importance of global anchor points for survey knowledge acquisition (Steck & Mallot, 2000; Li et al., 2014; Li et al., 2016; Schwering et al., 2017). In order to test these hypotheses, we conducted a virtual reality study in which participants navigated predetermined routes through cities with different landmark configurations and either with or without time pressure.

Human stress response is multidimensional

Stressful situations are common in human everyday life. For example, stress may occur when we are struggling with time pressure (Wahlström, Hagberg, Johnson, Svensson, & Rempel, 2002) or when our performance is evaluated (Zeidner, 1998). A dominant view in neuropsychology defines stress as threats to the homeostasis of an organism that require an adaptive response (Levine, 2005). This response is characterized by a complex interplay of physiological and psychological processes. On the physiological level, stress engages two neurobiological systems. First, stressors engage the sympathetic nervous system (SNS), which regulates vital physiological states such as changes in heart rate variability (Burg & Pickering, 2011) and sweat production (Boucsein, 2012). Second, stressors engage the hypothalamic-pituitary-adrenal axis (HPA), an endocrine system through which glucocorticoids (GCs) are secreted (de Kloet , Joëls, & Holsboer, 2005). A major behavioral role of the activation of these systems is a short-term increase (from seconds to minutes) in energy production required for immediate survival (Sapolsky, 1992).

Beside physiological activation, stress is represented on a psychological level and characterized by cognitive, motivational, and emotional processes. Attempts to connect these various aspects have resulted in theories that define a small set of core dimensions (e.g., Russell & Barrett, 1999; Watson & Tellegen, 1985; Thayer, 1989). In the circumplex model of affect, stress is defined as the combination of two bipolar dimensions, arousal and valence (Russell, 1980; Russell & Barrett, 1999). According to this theory, arousal is a psychological concept that refers to the extent to which one feels activated. Valence describes the range of one's well-being from pleasure to displeasure. According to this framework, stress is characterized by heightened arousal and negative/unpleasant valence (e.g., Russell & Barrett, 1999). Although arousal and valence dimensions do not exhaust the multifaceted nature of emotion (Russell & Barrett, 1999), researchers can use them to describe and identify common underlying characteristics. Both dimensions, arousal and valence, can be assessed by either physiological or self-report measures, although these two types of measures sometimes conflict (Levenson, 2014).

From a physiological perspective, arousal can also be assessed using electrodermal activity (EDA; e.g., Figner & Murphy, 2011). EDA is used to describe changes in the electrical properties of the skin that result from sympathetic arousal. Similarly, positive and negative valence can be inferred from changes in muscle activity related to specific facial expressions (i.e., facial electromyography or fEMG; e.g., Fridlund & Izard, 1983; Witvliet, 2001). The advantages of behavioral (fEMG) or physiological measures (EDA) are that they can be assessed continuously and noninvasively while participants perform a particular task. However, from a psychological perspective, the assessment of affective states should also be tied to individual appraisal processes (Lazarus & Folkman, 1984) because the same task or event can be perceived by different individuals in different ways and elicit different affective responses. The Dundee Stress State Questionnaire (DSSQ) is a self-report measure that differentiates between three underlying aspects of the stress response, distress, task engagement, and worry (Matthews et al. 1999). Distress (high arousal and negative valence) is a psychological state that binds together energetic arousal and negative valence (Matthews, Szalma, Panganiban, Neubauer, & Warm, 2013). High distress levels have also been associated with poorer working memory functioning (Matthews & Campbell, 2010). The key drivers of the distress response are high task workload and time pressure (Matthews et al., 2002; Hockey, 1997). In contrast, task engagement is a mental state of high arousal and positive valence and results from the perception of the task to be challenging and interesting (Matthews et al., 1999). In addition, worry is defined as self-focused attention and the tendency to have intrusive thoughts. Increasing levels of worry indicate that an individual may be more inclined to allocate attention to some aspects of self-evaluation (Matthews et al., 2002). Given that stress responses are strongly driven by context, we argue that understanding the impact of stress on survey knowledge acquisition requires an experimental manipulation that is relevant for everyday navigation such as time pressure. As opposed to extraneous stressors, navigation under time pressure may elicit stress responses that are governed by the nature of the task itself (Matthews et al., 2002). The effect of time pressure experienced during navigation is not well understood, but prior research has demonstrated that time pressure can increase the psychophysiological responses of individuals in general. For example, Wahlström and colleagues (2002) asked participants to complete simple text editing tasks in time pressure and no time pressure conditions. They observed increased physiological (blood pressure, heart rate) and psychological (mood ratings) responses under time pressure. For the remainder of this paper, we distinguish between the concept of acute stress and the measurement of specific aspects such as distress, task engagement, worry, arousal, and valence.

Spatial knowledge acquisition under stress

The general cognition literature has demonstrated that many cognitive functions are sensitive to acute stress. Acute stress has been shown to impact attention (e.g., attentional scope, selective attention), memory (e.g., the acquisition, consolidation, and retrieval of memory), and learning (goal-directed or habit learning; Sandi, 2013). Moderated by these cognitive functions, there is also evidence that acute stress can affect navigation (e.g., Thoresen et al., 2016; Gardony, Brunyé, Mahoney, & Taylor, 2011) and spatial knowledge acquisition.

One study on stress and spatial knowledge acquisition attempted to affect spatial learning by exposing a subset of participants to a loud, unpredictable noise (Evans et al., 1984). Participants viewed videos of walks through urban environments with or without salient landmarks. To assess spatial learning performance, the researchers asked participants to place photos from the video walkthrough on a large piece of paper in their respective locations. Participants exposed to environments with salient landmarks performed significantly better than participants exposed to environments without salient landmarks, but the (seemingly stressful) noise manipulation eliminated any advantage provided by landmarks (Evans et al., 1984). Unfortunately, the extent to which the observed effect is attributable to stress (as typically defined using physiological or self-report measures) is unclear.

In addition, Richardson and Tomasulo (2011) observed a negative effect of a stressful task on the speed with which participants performed a spatial memory task (but not their accuracy) after navigation through a virtual environment. One group of participants was first instructed to trace a figure viewed in a mirror, and another group of participants watched a nature video. Then, each of the participants was asked to learn the locations of target objects along different paths in a virtual environment. The researchers assessed spatial learning by asking participants to point to each target object after being teleported to each other target object. Physiological and self-report measures were used to assess the stress level of the two experimental groups (Richardson & Tomasulo, 2011), but only self-report measures verified a difference between the groups.

In contrast, Duncko and colleagues (2007) found that exposing participants to a cold pressor procedure (i.e., placing a participant's hand in cold water) before navigation through a virtual environment can actually improve spatial learning. Participants performed a virtual reality version of the Morris water maze task in which they were asked to navigate towards a particular location as quickly as possible over a series of trials. The results revealed that participants exposed to the cold pressor procedure navigated towards the goal location with significantly smaller heading errors and fewer overall failures. Duncko and colleagues (2007) also verified stress induction as a significant increase in heart rate in the cold pressor group. To our knowledge, all previous studies that investigated the relationship between arousal (or stress) and navigation employed a seemingly stressful task before navigation rather than manipulating the navigation task to be more stressful itself. An alternative approach (adopted for the present study) is to attempt to manipulate stress using time pressure and measure arousal physiologically during the navigation task. Such an approach may also help elucidate the more general cognitive mechanisms underlying a possible relationship between stress and navigation.

Working memory

Working memory is composed of the cognitive structures that maintain information in an active state via rehearsal and that retrieve information for a short period of time (Humphreys & Revelle, 1984). Prior research indicates that information that is presented simultaneously (rather than sequentially) is easier to encode and represent in working memory (e.g, Blalock & Clegg, 2010; Allen, Baddeley, & Hitch, 2006; Lecerf & de Ribaupierre, 2005). In general, acquiring survey knowledge by navigating large-scale environments requires the integration of visuospatial information over different views and over time in working memory (Friedman & Waller, 2008; Hegarty et al., 2006; Meilinger et al., 2008; Wen, Ishikawa & Sato, 2011; Labate, Pazzaglia, & Hegarty, 2014). The mental integration of environmental objects (e.g., routes and landmarks) is typically sequential in nature because they are limited by their visibility. However, global landmarks can be visible from different points along the route (often simultaneously). Because of this potential advantage for global landmarks viewed simultaneously, we hypothesize that survey knowledge acquisition might be more accurate for global landmarks than local landmarks. Prior research suggests that working memory functioning is affected by time pressure and other stressful situations (Morgan, Doran, Steffian, Hazlett, & Southwick, 2006). During stress, activation of the sympathetic nervous system (i.e., arousal) is accompanied by an engagement of the prefrontal dopamine system, which releases norepinephrine. High arousal and high doses of norepinephrine can lead to impairments of working memory functioning (Arnsten & Li, 2005; Humphreys, Lynch, Revelle, & Hall, 1983). Similarly, the hypothalamic-pituitary-adrenal axis exerts glucocorticoids during episode of acute stress. These hormones have been shown to impair the optimal functioning of working memory (e.g., Oei et al, 2006; Schoofs, Preu, & Wolf, 2008). Depending on the way stress is interpreted (e.g., as worry, distress, or engagement) and working memory is measured, acute stress has been described as facilitating and impairing working memory in different ways (Matthews et al., 2013; Jols, Pu, Wiegert, Oitzl, & Krugers, 2006). Specifically, complex tasks that require users to actively maintain and update incoming information in working memory have consistently found impairments under stress (Lupien, Gillin, & Hauger, 1999; Owen, McMillan, Laird, & Bullmore, 2005; Oei et al., 2006). For example, stress has been found to impair performance on an n-back task (Owen et al., 2005). For this task, participants needed to monitor a sequence of briefly presented stimuli and respond under time pressure whether the currently presented stimulus is identical to the stimulus presented n trials before. Similarly, an impairment of working memory should be particularly detrimental for the mental integration of local landmarks (presented sequentially) compared to global landmarks (presented simultaneously).

Attentional narrowing and global landmarks

Stress and heightened arousal can narrow attention either towards the arousing stimulus at the expense of less relevant stimuli or towards central stimuli at the expense of peripheral stimuli (see Levine & Edelstein, 2009, for a review). While attentional narrowing is often related to improved memory for arousing stimuli (Christianson & Loftus, 1991; Kensinger, Garoff-Eaton, & Schacter, 2006; Loftus, Loftus, & Messo, 1987), other studies examine attentional narrowing after placing participants in a state of heightened arousal and assessing their memory for neutral stimuli (Brunyé, Mahoney, Augustyn, & Taylor, 2009). With this approach, attentional narrowing has been associated with a processing bias towards task-relevant information and with the focusing of attention towards spatially central information (compared to peripheral stimuli). Following the metaphor of a spotlight (Posner, Snyder, & Davidson, 1980), researchers found that negative affective states can reduce accuracy and increase response time for detecting peripheral visual targets (e.g., Callaway & Dembo, 1958; Reeves & Bergum, 1972). Similarly, positive valence has been associated with an increase in the processing of spatially distant distractors (Rowe, Hirsh, & Anderson, 2007). While these experiments investigated the spatial extent of attentional focus on a 2D plane in figural space, recent research has expanded the zoom-lens metaphor of attentional narrowing to include 3D environmental context. For example, Gardony and colleagues (2011) demonstrated that high arousal states can influence the use of near and far landmarks for navigation in virtual reality. In their study, participants in low arousal states used distant landmarks (i.e., in the spatial periphery) more efficiently for navigation than participants in high arousal states (Gardony et al., 2011).

Attentional narrowing can result in either enhanced performance or reduced performance, depending on the demands of the task and the context (Staal, 2004). The ability to ignore irrelevant information may improve learning performance, but in some cases, it can deteriorate learning performance. Inattention to global environmental cues might be disadvantageous for spatial learning because global cues serve as orientation beacons (Steck & Mallot, 2000) that impose an absolute reference frame (O'keefe & Nadel, 1978), help users align spatial information, and determine the relative location of routes and landmarks in the environment (Gunzelmann & Anderson, 2006; Delikostidis et al., 2013). With these roles in mind, we defined global landmarks for the present study as peripheral and highly salient environmental cues that can be observed from a large portion of the environment and remain relatively constant in relation to the short distances travelled by the observers (Steck & Mallot, 2000).

Thus, there are at least two theoretical reasons why one would expect stress to adversely affect landmark-based, survey knowledge acquisition. Specifically, stress may disrupt the integration of local spatial information over time via working memory and/or reduce attention to global landmarks via attentional narrowing. In order to test these hypotheses, we conducted a virtual reality study in which we manipulated participants' attention towards local or global landmarks and whether the experimental situation was more or less stressful. EDA and fEMG data was collected while participants navigated through virtual cities from a first-person perspective. After each navigation trial, survey knowledge acquisition was assessed using judgments of relative direction.

Method

Participants

The study was conducted in German. Participants were recruited via two local online advertising services in Zurich. Specifically, we used the psychology recruitment server from the University of Zurich (https://www.psychologie.uzh.ch/probandenserver/) and the online market place for University of Zurich alumni (https://marktplatz.uzhalumni.ch/). Fifty-three people between the ages of 18 and 36 participated in the study for monetary compensation. Forty-eight of these participants completed all of the experimental tasks ($M_{\text{age}} = 25.8$ years, $SD_{\text{age}} = 6.2$, 24 women). Five participants aborted the study because of slight nausea. All of the procedures performed in this study were in accordance with the ethical standards of the Swiss Psychological Society and the American Psychological Association.

Materials

Apparatus. This experiment employed a virtual reality system called the CAVE that simulates binocular vision with the stereoscopic synchronization of active shutter glasses. Participants' head movements were tracked using infrared emitters attached to the shutter glasses and four optical sensors that were mounted to the top corners of the display screens. Ultra-short-throw projectors generated images with 1280x800 pixels at 120 Hz frequency on three screens. Each screen was 3120 mm wide and 1950 mm tall. These screens were located in front, to the left, and to the right of the participant. Figure 1 shows the CAVE setup with a participant sitting on a chair that was 30 cm back from the center of the system. The participant's viewpoint in the CAVE was offset 60 cm above the position of the shutter glasses. Participants navigated through virtual cities at 3.8m/sec using a wireless one-handed joystick device (i.e., WorldViz Wand). Physiological measures were recorded with transmitter modules (i.e., BioNomadixx) attached to the participant's wrist for EDA and head for facial EMG. These modules were wirelessly connected to the MP150 stationary acquisition unit (Biopac System Inc., GA, USA; https://www.biopac.com) via a local area network. At the participant's hand and face, 15 cm electrode leads connected each transmitter module to 24 mm disposable hydrogel electrodes (Ag-AgCl sensors). The experimental procedure was written in Python and rendered with Vizard 5.6 (WorldViz, Santa Barbara, CA, USA; https://www.worldviz.com). The city models were designed using City Engine 2014 (Esri, CA, USA; http://www.esri.com/software/cityengine). Physiological data acquisition and fEMG data analysis was conducted using AcqKnowledge 4.4 (Biopac Systems Inc.). EDA data was analyzed using LedaLab, a Matlab-based software for the analysis of skin conductance data (Benedek & Kaernbach, 2010). Using network data transfer, physiological recordings from AcqKnowledge were synchronized in real-time with the experimental procedure from Vizard.

Virtual Environments. In total, we created nine environments that combined three city models with three landmark sets. Each of the three city models had an area between 0.4 km^2 and 0.8 km^2. Building models consisted of low-rise buildings with heights between 5 m and 15 m. The street networks contained intersections with crossing angles between 65° and 115°, and the distances between intersections were between 20 m and 140 m. The sidewalk widths of all streets were constant at 3.5 m. Street widths were either 3.5 m, 7 m, or 10.5 m. There were no slopes, hills, or mountains inside or outside of the city area. Each city's route consisted of six turns (three left and three right turns). Figure 2 represents the street networks and the routes of each city.

Landmark sets were added to each city model with additional low-rise buildings (5 m to 15 m) located along the route (i.e., local landmarks) and/or high-rise buildings

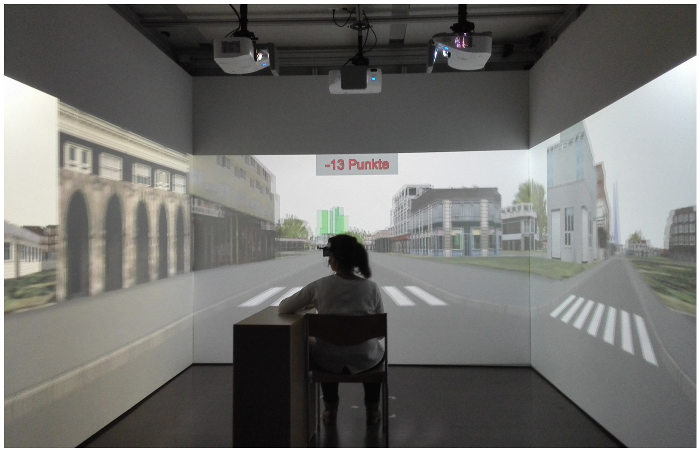

Figure 1. : Photograph of the CAVE from the experimenters viewpoint during the navigation task.

(80 m to 100 m) located in the distance (i.e., global landmarks). Local landmarks were restricted in visibility, and participants could not view more than one at a time. In contrast, global landmarks were visible from multiple locations along the route, and participants could often view more than one at a time. Figure 3 includes a screenshot of each of the three landmark sets within one of the three cities. In the local (without global) landmark condition, four local landmarks were added and highlighted. In the global (without local) landmark condition, four global landmarks were added and highlighted. In the local (with global) landmark condition, four local and two global landmarks were added, but only local landmarks were highlighted. We added only two global landmarks in the local (with global) landmark condition so that each individual landmark was more salient. Highlighted landmarks had distinct and intense colors and unique geometry. In contrast, non-target buildings had city textures with low color intensity.

Navigation Aid. During navigation, participants could call a navigation aid that displayed the route to the destination on top of a planimetric map. This map was displayed on the front screen of the CAVE and included a 0.071 km^2 section of the city (1:106 map) centered at the location of the user. The map indicated the street network, the highlighted route, and the location of the user in the virtual environment (see Figure 4). Buildings were not displayed on the map. Map information was oriented track-up. When the navigation aid was displayed, the side screens turned white, and movement through the virtual environment was disabled. In general, the functionalities of this navigation aid were inspired by contemporary designs and aimed to facilitate route-following while hindering landmark and survey learning directly from the map itself.

Judgments of Relative Direction. Judgments of relative direction (JRDs) involve mentally accessing the spatial relationships among three locations and attempting to accurately determine their relative direction (Shelton & McNamara, 2004). For each JRD, participants saw instructions on the front screen of the CAVE that displayed three different landmark buildings rotating around their vertical axis. These landmarks were depicted as rotating

Figure 2. : The street network of each city from a top-down perspective. The white lines represent streets. The blue lines depict the predefined route for each city. "S" represents the starting point of each route, and "E" represents the end point. The black dashed lines represent the accessible area within each environment. Participants entered the virtual city along the path indicated by the black arrow.

Figure 3. : Screenshots representing the three landmark conditions. (a) In the local (without global) landmark condition, only local landmarks were added and highlighted. (b) In the global (without local) landmark condition, only global landmarks were added and highlighted. (c) In the local (with global) landmark condition, both local and global landmarks were added, but only local landmarks were highlighted. The key comparisons across these conditions are between (a) and (b), assessing the accuracy of acquiring local and global landmark knowledge, and between (a) and (c), assessing the impact of global landmark presence on the accuracy of acquiring local landmark knowledge.

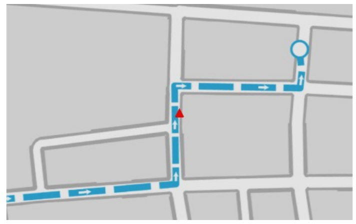

Figure 4. : Screenshot of the track-up navigation aid. The red triangle indicated the location of the participant in the virtual city. On top of the blue route, white arrows indicated the correct direction along the route to reach the destination. The destination was indicated as a blue circle.

because the façades of buildings are recognized better from an experienced view than from an unfamiliar view (Christou & Bülthoff, 1999). The instructions asked participants to imagine standing at a first landmark, facing a second landmark, and pointing to a third landmark. In the local (without global) and global (without local) landmark conditions, the three landmarks that constituted a single JRD task were randomly chosen from all 24 possible permutations. However, triples that resulted in a symmetric angle (e.g., -60° and 60°) were paired, and only one triple of each pair was randomly chosen for the task. For the local (with global) condition, eight additional triples were randomly chosen. In these additional trials, participants were asked to imagine standing at a local landmark, facing a second local landmark, and pointing to a third global landmark.

After the JRD instructions for each trial, participants were presented with a pointing screen that showed a white cross on a black background in the center of the front screen of the CAVE (Figure 5b). This white cross represented the reference direction to the second landmark. A white square was depicted on the floor in the center of the cave and represented the reference location of the first landmark. To complete the JRD, participants held the pointing device in the estimated direction of the third landmark and confirmed their decision by pressing a button on the pointing device. The orientation of the device was tracked by an internal measurement unit and the four optical sensors.

Questionnaires and Spatial Orientation Test. We also administered four types of questionnaires. First, orientation strategies were assessed with the Fragebogen Räumliche Strategien (FRS) questionnaire (Münzer & Hölscher, 2011). The FRS questionnaire focuses on the extent to which individuals rely on landmark-, route-, or survey-based strategies. Second, we administered a shortened version of the gaming questionnaire (items 1,2,3,5) originally developed by Terlecki and Newcombe (2005). Third, simulator sickness was assessed using the Simulator Sickness Questionnaire (SSQ) developed by Kennedy, Lane, Berbaum, and Lilienthal (1993). For the SSQ, participants rated 16 symptoms on a 4-point scale from absent to severe that were then used to generate scores for three simulator sickness subscales (i.e., nausea, disorientation, and oculomotor). Fourth, self-report measures of stress, engagement, and worry were assessed with the Short Stress State Questionnaire (SSSQ; Helton, 2004), which is a short version of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999). Based on the testing platform hypothesis (Šašinka, Morong, & Stachoň, 2017), we also administered an online version of the spatial orientation test from Hegarty and Waller (2004).

Procedure

Participants were tested individually. Before the experiment, participants completed an online questionnaire on demographics (i.e., age, gender, and handedness), the gaming questionnaire, and the FRS questionnaire. After arriving at the laboratory, participants received a standardized overview of the upcoming experimental tasks that was read aloud by the experimenter. Then, participants provided informed consent and completed the spatial orientation test from Hegarty and Waller (2004) on a computer screen. Subsequently, the experimenter attached the electrodes to the participants' fingers (EDA) and face (fEMG). EDA electrodes were placed at the medial phalanges of participants' index and middle fingers (Figner & Murphy, 2011), and fEMG electrodes were placed at the cheek (over the zygomaticus major), between and above the eyebrows (over the corrugator supercilii; Fridlund & Cacioppo, 1986), and on the upper forehead as a reference electrode (van Boxtel, 2010). At the EDA electrode sites, a light abrasive skin treatment was applied to lower skin impedance and moisten the underlying skin (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). For improving the fEMG signal, the fEMG electrode sites were cleaned with a mild alcohol wipe. Once the electrodes were attached and calibrated, the experimenter verified electrode impedance and checked their functionality. Then, participants rested for two minutes to ensure the hydration of the skin by the gel. Then, participants watched a two-minute nature video projected on the front screen of the CAVE. Physiological data was recorded during this nature video in order to later account for individual differences in physiological reactivity to acute stressors (e.g., Ulrich, 1981). Afterwards, participants read written instructions about the upcoming tasks, and the experimenter led the participants into the CAVE where participants sat on a chair and put on the 3D shutter glasses (Figure 5a). Then, participants were familiarized with the experimental tasks and the apparatus in a training phase. During this phase, the experimenter led participants through all components of an experimental trial (e.g., navigation, map use, and the JRD task). We designed an extra city specifically for this training trial.

After the participant had no further open questions, the experimenter started the main experiment. The main experiment consisted of three blocks. Each experimental block consisted of a train ride, a navigation task, and a pointing task. During the train ride, participants were sitting in a virtual train waiting to arrive at the navigation destination. The train ride was intended to increase the believability of the navigation task (Freeman, Lessiter, Pugh, & Keogh, 2005), which can enhance users' emotional responses to the displayed content (Riva, Waterworth, & Waterworth, 2004). After the 30-second train ride, the participant's viewpoint was automatically moved out of the virtual train to begin the navigation task. During the navigation task, participants were instructed to follow a predefined route as quickly as possible and to memorize the relative locations of the highlighted landmarks as accurately as possible. The number of highlighted landmarks was unknown to the participants. Participants were explicitly instructed not to prioritize one of these two tasks. Participants were also asked not to leave the route marked on the navigation aid. When a participant left the route accidentally, a message appeared on the front screen asking them to return to the marked route at the location they left the route. Participants finished the navigation task when they arrived at the destination. Participants' survey knowledge

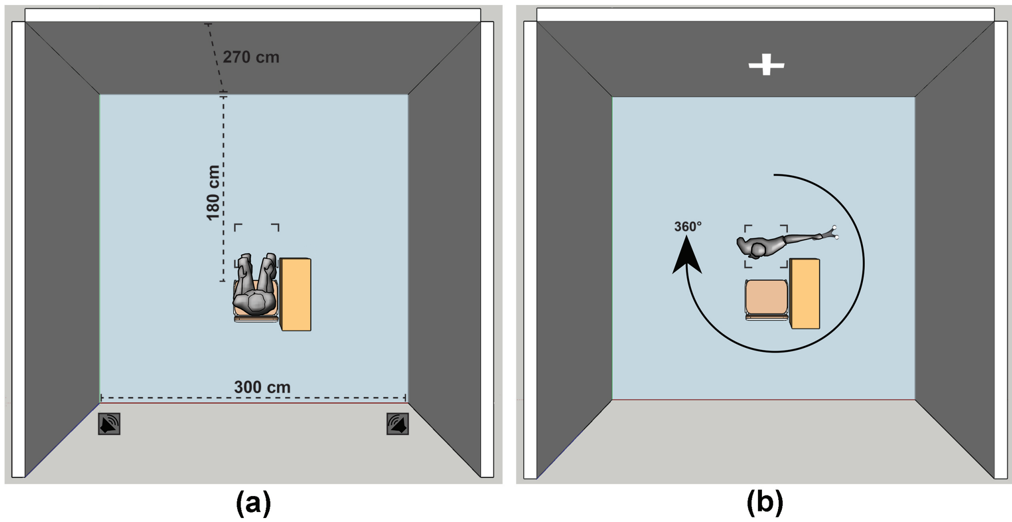

Figure 5. : The CAVE illustrated from a top-down perspective. (a) During the nature video, the training task, and the navigation task, participants sat on a chair fixed 30 cm back from the center of the CAVE. A small shelf was used as an armrest for the non-dominant hand where the EDA electrodes were attached. (b) During the JRD task, participants stood upright in the middle of the CAVE. The black square marked on the floor in the center of the cave, and the white cross, depicted at the front screen, represented the reference point and reference direction, respectively, for the JRD.

was then assessed using JRDs. Participants completed 12 (or 20) JRDs (depending on landmark condition). After each JRD, participants indicated their pointing confidence on a continuous Likert scale between very unconfident and very confident. Pointing accuracy and confidence were both recorded automatically by the system. Before and after the main experiment, participants were asked to complete the SSQ (Kennedy et al., 1993) and the SSSQ (Helton, 2004), indicating their mental states immediately before and during the last minute of the experiment.

Design & Analysis

Design. This experiment included two independent variables in a 2 (time pressure / no time pressure) x 3 (local without global landmarks / global without local landmarks / local with global landmarks) mixed factorial design. Participants were randomly assigned to either the time pressure or no time pressure group (i.e., between-subjects) but completed all three landmark conditions (within-subjects in a counterbalanced order). Dependent variables included questionnaire data, the survey knowledge measure (i.e., JRD accuracy), and physiological measures (i.e., EDA and fEMG).

Time pressure manipulation. Participants in both the time pressure and no time pressure conditions were asked to reach the destination as quickly as possible and learn as accurately as possible. In the time pressure group, two scores were introduced. First, we introduced a learning score that was not displayed, although participants were instructed that it was related to JRD performance. Second, participant's time score began at 100 points and decreased by 1 point every 10 seconds during navigation. After losing every 10 points, the current time score was highlighted, and a beep sound was played. The deduction of points began during the train ride when participants could not yet act to ameliorate the situation. Time pressure was also emphasized with an audio announcement regarding the delay of the train and a clock ticking sound that was played constantly in the background. This audio announcement began with the well-known jingle of the Swiss railway company. Participants in the time pressure group were told before the experiment that their monetary compensation would depend on both scores and varied between 10 CHF and 20 CHF. The framing of the incentive was negative, so participants began with 25 CHF and could lose between 5 CHF and 15 CHF. In the no time pressure group, participants had no performance scores, and the endowment was fixed at 20 CHF.

Survey Knowledge Measures. Survey knowledge was assessed as the accuracy of JRDs. JRD accuracy was defined as the absolute angular difference between the estimated direction and the actual direction of a target relative to the reference landmarks. Angular errors could vary between 0°(very accurate) and 180°(very inaccurate). The data were analyzed using mixed 2 (between) x 2 (within) ANOVAs if the assumption of homogeneity of variance was met. Greenhouse-Geisser corrections were applied if sphericity was violated. If the assumption of homogeneity was not met, absolute angular errors were submitted to an aligned-rank transformed non-parametric analysis of variance (ART ANOVA; Wobbrock, Findlater, Gergle, & Higgins, 2011). The ART ANOVA allows accurate treatment of nonparametric data by aligning the dependent variable with respect to each main and interaction effect before converting the data to ranks (Wobbrock et al., 2011). ANOVAs were conducted on two different data subsets which contained observations from condition a (local without global) and b (global without local) or observations from condition a (local without global) and c (local with global). The former comparison (a versus b) addresses the accuracy of acquiring survey knowledge from local and global landmark configurations. The latter comparison (a versus c) addresses the impact of global landmark presence on the accuracy of acquiring survey knowledge from local landmark configurations.

Psychophysiological Measures. The data obtained from both EDA and fEMG signals were extracted at 1000 Hz. The experimental script automatically logged predefined events (e.g., the start and end of a navigation trial) in the physiological recordings. EDA data was then downsampled to 10 Hz. This procedure attenuates noise and smooths the data. There were no post-hoc filters applied to the EDA signal. By means of a continuous decomposition analysis (CDA), we decomposed EDA data into continuous tonic and phasic activity (Benedek & Kaernbach, 2010). For the present study, we assessed arousal level over longer time spans from approximately three to six minutes (i.e., the duration of the navigation task). High arousal states were operationalized as a change in the tonic component of EDA (i.e., skin conductance level or SCL) or as an increase of non-specific skin conductance responses per minute (nSCRs/min; Boucsein, 2012). Hence, statistical analysis of this EDA data was based on computing intra-individual changes for both mean tonic SCL and mean nSCRs per minute. Difference values were computed by subtracting the individual mean values of the navigation conditions from the baseline condition. Baseline normalized mean scores for EDA were then submitted to independent-samples t-tests (two-tailed) in order to test if time pressure condition increased arousal.

A FIR bandpass filter (28Hz – 500Hz) was applied to the raw fEMG signal using a Blackman window. The frequency cut-offs are based on the predominant frequency range of fEMG signals (van Boxtel, 2010). Then, we computed the root-mean-square (RMS) envelope of both muscles' signals using a moving window over 100 samples. To derive meaningful insights about the individual valence dimension of a participant's emotional state, we computed the change factor from baseline. More specifically, we divided the mean signal (e.g., corrugator activity) measured during a navigation phase by the mean signal of the participant's baseline measurement. Valence values were then computed by subtracting the change value of corrugator activity from the change value of zygomaticus activity.

Questionnaires and Spatial Orientation Test. For the Short Stress State Questionnaire, we define the comparisons of the experimental treatments (time pressure and no time pressure) as the main goal of the measure and the comparisons of the pre and post measurements as secondary analysis. Therefore, we performed separate Bonferroni adjustments for each of these family of tests (Bender & Lange, 2001). For the SSSQ main analysis, six independent groups t-tests (two-tailed) were conducted with a Bonferroni adjusted alpha level of .0083 per test (α altered = .05/6), and for the SSSQ secondary analysis, six paired t-tests (two-tailed) were conducted with a Bonferroni adjusted alpha level of .0083 per test (α altered = .05/6). For the Simulator Sickness Questionnaire, we conducted four paired-sample t-tests (two-tailed) with a Bonferroni adjusted alpha level of .0125 per test (α altered = .05/4). In the spatial orientation test, the item score was the absolute deviation in angular degrees between the participants response and the correct direction to the target. A participants total score was the mean error across all items.

Hypotheses. First, we hypothesized that the integration of global landmark configurations in a survey representation should be more accurate (lower JRD error) than the integration of local landmark configurations. Second, we expected the learning advantage of global landmarks to be larger in the time pressure group in which working memory resources should be impaired. Third, we hypothesized that the mere presence of global landmarks (that are not highlighted) should improve participants' survey representations (lower JRD error) only when participants navigate without time pressure. Otherwise, we expected inattention to global landmarks to reduce the beneficial effects of survey knowledge acquisition.

Results

General Sample Description

Overall, 47 of 48 participants completed the video gaming experience questionnaire. Eighteen participants reported playing video games on a regular basis. Of these, three participants reported playing once every half a year, seven participants reported playing monthly, and eight participants reported playing weekly. From leaving the virtual train until arriving at the destination, participants required 271.9 seconds on average. There was no significant difference in navigation time between the time pressure (M = 263.93, SD = 38) and no time pressure groups (M = 280.07, SD = 57.8), $t(79.3) = 1.60$, $p = .113$. On average, participants used the navigation aid for approximately 19.3 seconds during

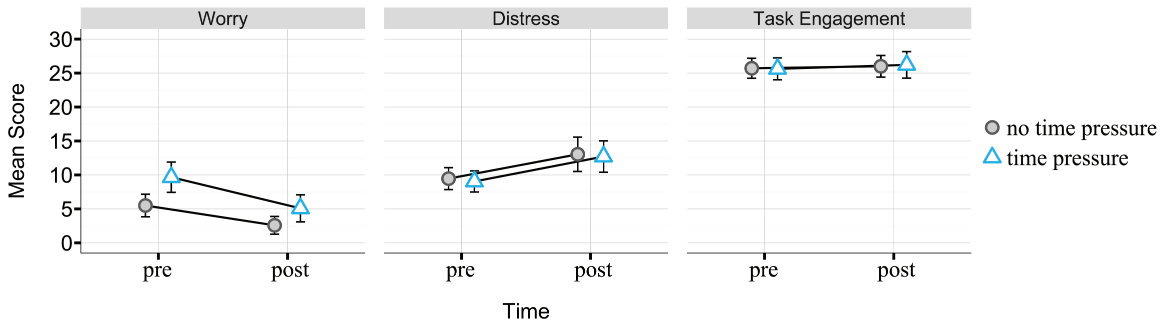

Figure 6. : Mean scores of the worry, distress, and task engagement subscales of the Short Stress State Questionnaire (Helton, 2004) in the experimental conditions. Dots represent means and error bars represent 95% confidence intervals. Among the three subscales, only pre-task worry ratings significantly differed between the time pressure and no time pressure groups.

a complete navigation trial. There was a significant difference in the ratio of navigation aid use over trial duration (the amount of time required to reach the destination) between the time pressure (M = 5.39%, SD = 2%) and no time pressure groups (M = 8.15%, SD = 5.5%), t(57.664)= 3.24, p = .0019.

Manipulation Check

Short Stress State Questionnaire. For the distress factor, there was not a significant difference between the groups, neither before the study, $t(46) = 0.38$, $p > .999$, nor after the study, $t(46) = 0.2$, $p > .999$. There was also not a significant difference of task engagement between time pressure and no time pressure groups, neither before the study, $t(46) = 0.08$, $p > .999$, nor after the study, $t(46)$ = -0.17, $p > .999$. Before the study, there was a significant effect for the worry subscale between the time pressure (M = 9.67, SD = 5.29) and no time pressure groups (M = 5.50, SD = 3.94), $t(46)$ = -3.10, p = .02, d = 0.89. After the study, worry was similar in the time pressure (M = 5.08, SD = 4.72) and no time pressure groups (M = 2.58, SD = 3.09), $t(46)$ = -2.17, p = .21.

Paired comparisons between pre- and post-task SSSQ scores revealed that there was no significant increase in self-reported distress from pre- to post-task assessment in the time pressure group, $t(23)$ = -2.74, p = .070, and in the no time pressure group, $t(23)$ = -2.64, p = .087. In addition, there was not a significant change in task engagement before and after the study in neither the time pressure group, t(23)= -0.76, $p > .999$, nor the no time pressure group, t(23)= -0.18, p = 0.857. In contrast, performing the navigation task significantly decreased worry. Participants in the time pressure group had a mean decrease in worry scores of 4.58 (SD = 4.19), $t(23) = 5.36$, $p < .001$, $d = 1.0$. Participants in the no time pressure group had a mean decrease in worry scores of 2.91 (SD = 2.76), $t(23) = 5.17$, $p < .001$, $d = 1.1$. Figure 6 depicts how participants in time pressure and no time pressure groups scored on the three SSSQ subscales before and after the experiment.

Physiological Recordings. The data of five participants were excluded from EDA analysis, and the data of one participant was excluded from fEMG analysis because a manual inspection of the data revealed many movement artefacts. As such, the EDA analyses were based on 43 participants.

Against our expectations, there was no significant effect of time pressure on the tonic level of skin conductance (after accounting for baseline) with similar scores for the time pressure (M = 1.99, SD = 1.89) and no time pressure groups (M = 1.8; SD = 1.00), $t(41) = 0.42$, $p = .676$. However, there was a significant difference in number of nonspecific skin conductance responses per minute (nSCRs/min) between time pressure conditions. More specifically, there was a higher frequency of nSCRs/min (after accounting for baseline) for the time pressure group (M = 1.14, SD = 9.39) than for the no time pressure group (M = -5.99, SD = 12.21), $t(41) = 2.15$, $p = .037$, $d = 0.66$.

There was no significant effect of time pressure on fEMG signal, with similarly negative valence scores (after accounting for baseline) in time pressure (M = -0.11, SD = 0.77) and no time pressure groups (M = -0.05, SD = 0.72), $t(44.964)$ = -0.25, $p = .8$.

Simulator Sickness. SSQ total scores revealed significant differences between pre-study (M = 13.01, SD = 13.78) and post-study (M = 28.52, SD = 24.01), $t(47)$ = -4,53, $p < .001$, $d = 0.64$. This effect is composed of a significant increase in reported nausea symptoms, $t(47)$ = -4.36, $p < .001$, $d = 0.61$, a significant increase in reported disorientation symptoms $t(47) = 5.48$, $p < .001$, $d = 0.59$, and a significant increase in reported oculomotor symptoms, $t(47)$ = -3.59, $p = .003$, $d = 0.51$. In general, the manipulation checks indicate that participants in the time pressure group may have been more physiologically aroused (in terms of nSCR/min) but not necessarily more distressed (in terms of the SSSQ and fEMG measures) than participants in the no time pressure group.

JRD Results

Overall, the 48 participants produced 2112 JRDs. Mean angular error was 51.3 (SD = 47.6). The middle 50% of the data (IQR) ranges from 13.8 to 67.5 angular error.

Time pressure and pointing to local and global landmarks. Absolute angular errors were submitted to an ART ANOVA with time pressure (with / without) and landmark type (local without global / global without local) as factors. This analysis revealed no significant main effect of time pressure, $F(1,46) = 3.77$, $p = .058$. Also, there was no significant main effect of landmark condition, $F(1,1102) = 0.49$, $p = .486$, or interaction, $F(1,1102) = 0.02$, $p = .325$. Inconsistent with our expectations, directional judgments for local landmarks were similarly accurate as directional judgments for global landmarks (Figure 7). The cell sizes, means, and standard deviations for the raw data of the 2x2 factorial design are presented in Table 1.

Time pressure and attentional narrowing. A mixed factorial ANOVA with time pressure (with / without) as a between-subjects factor and landmark condition (local without global / local with global) as a within-subject factor was computed for the mean absolute angular error of JRDs towards local landmarks. We did not observe a significant main effect of time pressure on absolute angular errors, $F(1,46) = 1.25$, $p = .27$. We also did not observe a significant main effect for landmark condition, $F(1,46) = 2.77$, $p = .1$, or an interaction, $F(1,46) = 0.004$, $p = .95$. Inconsistent with our expectations, directional judgments for local landmarks were not improved by the presence of global landmarks (Figure 8). The

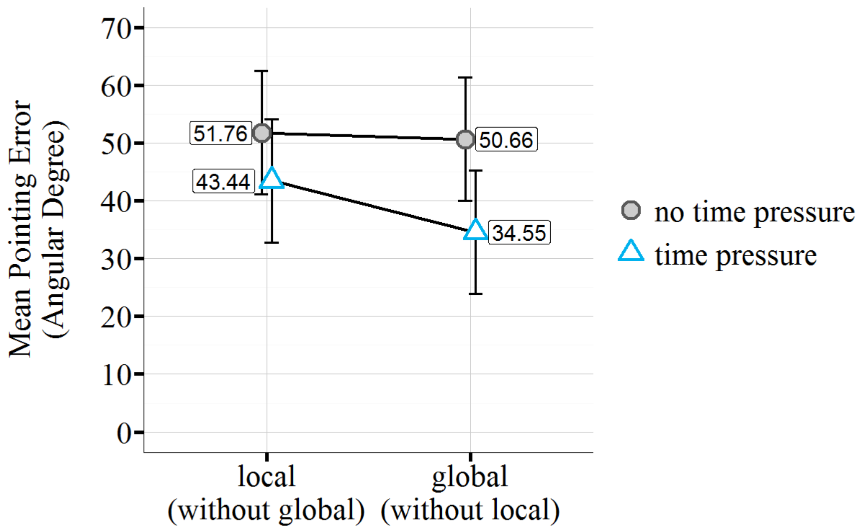

Figure 7. : This graph illustrates the accuracy of acquiring survey knowledge from local and global landmarks. There was no significant difference between participants JRD performance when judging between local or global landmark configurations. Similarly, there is no significant effect of time pressure on JRD performance. Dots represent means and error bars depict 95% confidence intervals.

Table 1:

The table depicts cell sizes, means, and standard deviations for the raw observations (angular error) of the local (without global) and local (with global) conditions.

	Local (without global)			Local (with global)			Marginal means		
	n	*M*	*SD*	n	*M*	*SD*	n	*M*	*SD*
No time pressure	12	51.76	49.20	12	50.66	46.78	24	51.2	47.96
Time pressure	12	43.44	44.70	12	34.55	34.84	24	39.00	40.28
Marginal means	24	47.60	47.14	24	43.6	41.99			

n = number of observations, M = mean, SD= standard deviation.

cell sizes, means, and standard deviations for the raw data of the 2x2 factorial design are presented in Table 2.

In the local (with global) condition, we also assessed the mean absolute angular error for JRDs towards global landmarks (that were not highlighted). There was no significant difference between the time pressure group (M = 62.15, SD = 51.30) and the no time pressure group (M = 68.15, SD = 48.48), $t(46)$ = 0.93, p = .360. However, a one-sample t-test showed that mean JRD error was significantly different from a mean absolute angular error of 90 (chance), $t(47)$ = -7.67, p < .001, indicating that participants acquired some knowledge about these landmarks.

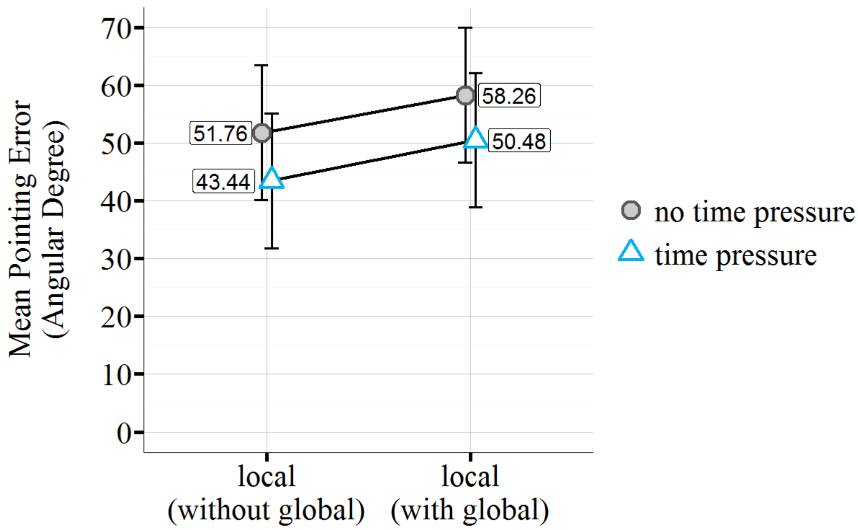

Figure 8. : This graph illustrates the null effect of global landmark presence on the accuracy of acquiring survey knowledge from local landmark configurations. Accuracy of directional judgments between local landmarks did not change when global landmarks were present or not. Similarly, there was no difference in JRD performance between time pressure and no time pressure groups. Dots represent means and error bars depict 95% confidence intervals.

Table 2:

The table depicts cell sizes, means, and standard deviations for the raw observations (angular error) of the local (without global) and local (with global) conditions.

	Local (without global)			Local (with global)			Marginal means		
	n	*M*	*SD*	n	*M*	*SD*	n	*M*	*SD*
No time pressure	12	51.76	49.20	12	58.26	49.75	24	55.01	49.54
Time pressure	12	43.44	44.70	12	50.48	48.83	24	46.96	46.90
Marginal means	24	47.60	47.14	24	54.37	60.50			

n = number of observations, M = mean, SD= standard deviation.

Spatial Abilities and Strategies

Overall, perspective taking ability was not significantly correlated with mean absolute angular error, $r(94) = .2$, $p = .051$. Furthermore, perspective taking ability was not correlated with mean absolute angular error for neither the local without global condition, $r(46) = .14$, $p = .35$, nor the global without local condition, $r(46) = .27$, $p = .07$. There were also no significant correlations between orientation strategies (FRS) and JRD error.

Discussion

The present study examined the effects of time pressure on survey knowledge acquisition for local and global landmark configurations during egocentric navigation in VR. After navigation, we assessed the accuracy of survey knowledge with judgments of relative direction (JRDs). Regarding the analysis, we first examined the effects of time pressure on the accuracy of JRDs for local landmarks (e.g., a shop along the route) and global landmarks (e.g., a tower in the distance). Specifically, we hypothesized that stress-related impairments of working memory have adverse effects on JRDs for local landmark configurations but have less adverse effects on JRDs for global landmark configurations. Second, we examined whether the mere presence of global landmarks supports survey knowledge acquisition for local landmarks. We hypothesized that the presence of global landmarks would facilitate survey knowledge acquisition for local landmarks, but only in the no time pressure group (i.e, attentional narrowing; Gardony et al., 2011). In the following, we will discuss the results, limitations, and implications of the present experiment individually for the two main research questions.

Comparison of local and global landmark learning

Against our expectations, we found no advantage of global landmark configurations for survey knowledge acquisition with or without time pressure. Similarly, Castelli and colleagues (2008) demonstrated that survey knowledge for global landmarks was not better than survey knowledge for local landmarks after navigation through a virtual labyrinth. However, in Castelli and colleagues (2008), both local and global landmarks were available concurrently, so participants could have used global landmarks as directional cues in order to mentally integrate other landmarks. In contrast, there are several studies that demonstrated that global landmarks facilitate survey knowledge acquisition during navigation (Li et al., 2016; Li et al., 2014; Schwering et al. 2017), but the learning tasks in these studies differed in important aspects from the present study. For example, Li and colleagues (2016) examined the impact of actively attending a single global landmark during navigation on the mental integration of other local types of spatial information, but the present study assessed the accuracy of mentally integrating multiple global landmarks into one coherent representation. Similarly, Li and colleagues (2014) and Schwering and colleagues (2017) examined survey learning after global landmarks had been displayed from a top-down perspective on navigation devices. In our study, the navigation aid did not depict landmarks, and survey knowledge was necessarily acquired from egocentric experience. To our knowledge, the present study was the first navigation study to compare the accuracy of survey knowledge towards multiple global landmarks to survey knowledge of multiple local landmarks.

Learning global landmarks in the present study was different from Li and colleagues (2014) and Schwering and colleagues (2017) because it required participants to mentally integrate spatial locations over time. This process of path integration (e.g., Klatzky, Loomis, Beall, Chance, & Golledge, 1998) may have been especially difficult for global landmarks because they were always placed in the distance instead of along the route. In contrast, the locations of local landmarks would have been easier to learn than global landmarks via path integration. If so, the effect of path integration may have counteracted the hypothesized advantage of global landmarks. Although this explanation is somewhat speculative, previous research has suggested that visual cues alone (e.g., optic flow, landmark piloting) may be sufficient for updating spatial positions and orientations (Kearns, Warren, Duchon, & Tarr, 2002; Riecke, Cunningham, & Bülthoff, 2006; May & Klatzky, 2000). Future studies should disentangle the advantage of local landmarks via path integration and the advantage of global landmarks via reorientation at the larger scale for navigation through a virtual environment.

Time pressure manipulation

We expected an even larger learning advantage for global landmarks under time pressure because working memory resources can be impaired under stress. Contrary to our expectations, we did not find an advantage for the mental integration of global landmark configurations, despite the heightened physiological arousal of participants under time pressure. The absence of a stress-related effect on spatial learning performance disagrees with other findings that indicate the improvement (Duncko et al., 2007) or impairment (Richardson & Tomasulo, 2011; Evans et al., 1984) of spatial knowledge acquisition under stress. In the present study, there was a trend that may have indicated an improvement for only global landmarks under time pressure. This lack of a significant effect could be due to low statistical power. Other possible explanations for this null effect include the extent to which the navigation task was easy to complete for both time pressure and no time pressure groups, the overall difficulty of the task used to assess survey knowledge (e.g., JRDs), and the possibility of time pressure tapping into emotions other than distress.

Time pressure may not have affected spatial memory if this particular manipulation only tapped the norepinephrine system and not the glucocorticoid system. Even though prior research has indicated that working memory functioning is affected by the norepinephrine system (e.g., Arnsten & Li, 2005), other research found evidence that impairment of working memory only occurs if the glucocorticoid system is simultaneously triggered (Elzinga & Roelofs, 2005). For the present study, this lack of neurobiological response patterns may be represented by the low self-reported levels of distress for both time pressure and no time pressure groups. Indeed, among the self-report measures, we only found an effect of group assignment on pre-task worry ratings. This pattern could be attributable to the instructions regarding participants compensation given before the experiment. In general, low self-reported distress may also indicate low workload (Matthews et al., 2002). Future studies can use a stronger manipulation of workload (e.g., spatial tapping; see Garden, Cornoldi, & Logie, 2002) and/or measure both physiological arousal and cortisol level directly. With respect to the difficulty of the task used to assess survey knowledge, additional training on the JRD task (before the main experiment and with different stimuli) may reduce the overall variability among individuals and increase statistical power.

In addition, self-reported simulator sickness might have introduced additional noise in the data. The ratings of participants indicated that they had symptoms of nausea, disorientation, and oculomotor problems. Future VR studies in CAVEs need to find efficient means to habituate participants to the simulator environment (Howarth & Hodder, 2008).

Attentional Narrowing

In the present study, the mere presence of global landmarks did not appear to improve survey knowledge acquisition for local landmark configurations (compared to when global landmarks were absent) for either the time pressure or the no time pressure group. This result indicates that visible global landmarks are either not used spontaneously during navigation or do not improve spatial memory for local landmark configurations. Previous research using different versions of the Morris water maze task (Gardony et al., 2011) have found that global landmarks help participants find hidden goal locations compared to searches with only local landmarks, but in the present study, the information provided by global landmarks may have been redundant with the information provided by other sources (e.g., navigation aid and/or optic flow via path integration). In addition, the participants may have allocated more attention to the navigation task than to the spatial memory task, as evidenced by the high JRD errors overall. In order to address this possibility, future research could focus on attention allocation during navigation through a large-scale virtual environment using eye tracking.

Future research may also systematically investigate the visibility and locations of global landmarks in different navigation contexts (e.g., stress, high working memory load, or assisted navigation). This research can contribute to navigation system design by illustrating the opportunities and challenges associated with learning different landmark configurations from an egocentric perspective. For example, future navigation systems may combine traditional static survey maps with dynamic components such as highlighting landmarks from an egocentric perspective (e.g., using augmented reality) or visualizing landmarks on a survey map using 3D icons. Previous research has indicated that static survey maps lead to better survey knowledge in the short term but may not confer an advantage in the long term (Thorndyke & Hayes Roth, 1980). With respect to future navigation system design, more variability in dynamic spatial stimuli acquired from egocentric perspective should lead to more flexible representations over a long period of time.

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